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W.R. Buchanan

GROUNDING BANKS

DETERMINING THE REQUIRED CAPACITY

By
L. L. Stahler
Florida Power & Light Company
Miami, Florida

Fall Conference - Engineering & Operation Section
Southeastern Electric Exchange, Tutwiler Hotel, Birmingham, Ala.
September 23-24, 1943

Grounding banks are used to establish a neutral on a delta system permitting the use of distribution transformers with a lower primary voltage and to supply ground current for relaying phase to ground faults.

A system neutral may be established by the use of an auto transformer with a delta tertiary winding, by the use of a wye-wye transformer with delta tertiary winding, by the use of a zigzag auto transformer or by the use of three single phase transformers connected wye-delta.

This discussion refers specifically to the use of three single phase transformers as a grounding bank although the data given are applicable to other types of transformers.

The usual practice in installing grounding banks is to use a bank having 33-1/3% of the kva capacity of the substation. This practice results in grounding banks of unnecessarily large capacity. In view of the present shortage of equipment it might be advisable to investigate all existing grounding bank installations as many of them could be replaced with banks of smaller capacity thereby releasing much needed equipment.

In determining the capacity required in a grounding bank three factors must be considered. These factors are: first, the maximum amount of unbalanced kva load which may be imposed on the bank for long periods of time; second, the maximum phase to ground fault kva which may be imposed on the bank for relatively short periods of time and third, the maximum rise above normal phase to ground potential which may occur on the unfaulted phases during a phase to ground fault. Before discussing these limiting factors it would be well to briefly discuss the action of a grounding bank. This can best be accomplished by the use of diagrams.

Refer to Fig. 1 which shows schematically the connections used in a wye primary - delta secondary grounding bank. No fuses are installed in the primary leads of the transformer since these transformers may be subjected to a momentary load equal to many times their rated capacity and any fuse which would not blow under these momentary loads would afford no protection to the transformer.

The secondary is connected delta and normally serves no load. The secondary of a grounding bank could be utilized to serve a load if it had excess capacity over and above that required in its normal function as a grounding bank. Generally speaking, the serving of load from a grounding bank can not be recommended since it would complicate relaying of the circuit under ground faults. With balanced voltage between phases and with balanced three phase load on the line no current flows in the grounding bank except that required to magnetize the transformers.

A primary phase to neutral fault near the grounding bank approaches very closely to the condition which would exist if the primary leads of one transformer in the grounding bank were shorted. Under such conditions the impedance of the faulted phase drops to a value approximating the short circuit impedance of the grounding bank transformer in that phase.

The resulting unbalanced voltage causes a circulating current in the delta secondary of the grounding bank. This circulating current causes an induced voltage in the primary of the shorted grounding bank transformer which induced voltage causes current to flow between the faulted phase and neutral, the current being inversely proportional to the sum of the impedances of the grounding bank and the faulted line section.

Fig. 2 shows the current flow in a grounding bank and in the distribution system under conditions of unbalanced load or phase to neutral fault. The unbalanced load or fault current is taken as 3I and each arrow in Fig. 2 represents I or $\frac{\text{Fault I}}{3}$. For convenience, the transformers in the grounding bank are assumed to have a transformation ratio of 1 to 1.

The unbalanced phase to neutral load divides equally between the transformers of the grounding bank, each transformer carrying one third of the total.

1. <u>Grounding Bank Capacity Required to Carry Unbalanced Loads on Distribution System</u>

The distribution of current in the grounding bank, upon occurrence of unbalance, (see Fig. 2) is such that the bank must have three phase capacity for continuous load equal to the kva of maximum unbalanced load.

The load unbalance on a distribution circuit may, under severe conditions, reach a momentary value, equal to 25% of the circuit load. The load unbalance on a substation feeding two or more distribution circuits will seldom, if ever, exceed 15% of the total substation load.

The accidental opening of either one or two (phase) conductors of a distribution circuit may impose a load on the grounding bank equal to 33-1/3% of the phase to neutral load on the circuit. This phase to neutral load includes all service supplied at single phase and all three phase service supplied from open wye-delta transformer banks.

From the foregoing it may be stated that a grounding bank should have a minimum capacity of not less than 15% of the total substation load and not less than 33-1/3% of the phase to neutral load on any one circuit served from the substation.

2. Voltage Rise in Unfaulted Phases During Phase to Ground Faults

The impedance of the grounding bank should be low enough to prevent excessive voltage rise on the unfaulted phases during a phase to ground fault. Fig. 3 shows the voltage rise which will occur on the unfaulted phases during phase to ground faults with various grounding bank impedances.

The grounding bank impedance (Z_0) is expressed as a ratio to the positive sequence impedance (Z_1) of the supply system or $\frac{Z_0}{Z_1}$, where Z_1 is the positive sequence, or three phase, impedance of the system expressed in terms of some convenient kva base. Z_0 is the zero sequence impedance of the distribution system to the fault location. In the following discussion the fault is assumed to occur at the grounding bank bus under which condition Z_0 includes only the zero sequence impedance of the grounding bank.

From Fig. 3 it is seen that a grounding bank impedance equal to nine times the positive sequence impedance of the system will result in over-voltage on the unfaulted phases of 50%.

For nearly all customer-owned equipment, particularly lamps and motors, a voltage rise of 50% is not objectionable provided the fault is cleared within a very short time. It should be pointed out that the voltage rise shown on Fig. 3 is based on the assumption that the phase to ground fault occurs at the substation bus. The voltage rise will decrease rapidly as the distance between the substation bus and the fault location increases.

A voltage rise of 50% above normal is about the maximum permissible value due to the 60 cycle discharge characteristics of the lightning arresters commonly used on wye distribution systems.

3. Self Protection of Grounding Bank

The impedance of the grounding transformer bank must be such that the ground current will be limited to a value which the transformer can safely carry without damage during the time required by the oil circuit breaker to clear the circuit.

Curve A, Fig. 4 is a short time loading curve for distribution transformers as shown in G.E. publication GET-1008. This curve is based on the assumption that the transformers are deenergized following the overloaded condition. This curve is not applicable to grounding banks which are subjected to recurring loads under fault conditions due to the reclosing of the oil circuit breaker. The oil circuit breaker will usually close twice after the initial opening before locking out.

Curves B and C, Fig. 4 are short time loading curves for power transformers under conditions of recurrent load. These curves are based on data taken from Table 1, page 1355, Transactions AIEE 1934, Vol. 53 in a paper entitled "Overloading of Power Transformers" and represents recommendations for incorporation into AIEE Standards No. 100. When determining the capacity required in a grounding bank the use of Curve B covering conditions of recurrent loads following no load is recommended. The use of Curve B rather than Curve C is justified since the possibility of a fault of maximum magnitude occurring during the time the grounding bank is fully loaded is very remote. Curve B has a safety factor inasmuch as there is little possibility of a fault of maximum magnitude being of two seconds duration. Relay and breaker action will normally limit faults of such magnitude to a duration of less than one second.

4. Method of Determining the Capacity Required in a Grounding Bank

To illustrate the method of determining the kva capacity required in a grounding bank assume the following conditions:

A substation has a positive sequence impedance (Z_1), at the distribution voltage bus, of 20% expressed in terms of a 20,000 kva base. This substation serves a total load of 6000 kva divided between three distribution circuits or 2000 kva per circuit. The phase to neutral load on each circuit is approximately 1500 kva. What capacity is required in a grounding bank at this substation?

a. Capacity Required for Continuous Load

It has been said that a grounding bank must have three phase capacity for continuous load equal to the kva of maximum unbalanced load. It has also been said that the three phase capacity of the grounding bank should be not less than 15% of the total load on the substation (when serving two or more circuits) and not less than 33-1/3% of the phase to neutral load on any one circuit.

The first limitation requires .15 x 6000 or 900 kva capacity in the grounding bank while the second limitation requires .333 x 1500 or 500 kva capacity in the grounding bank at the substation described.

b. Capacity Required for Short Time or Fault Loads

If the maximum phase to ground fault kva is to be limited to (N) times the grounding bank rating (see Fig. 4) the following calculation shows the method of determining the kva capacity required in the grounding bank, with transformers of various impedances, to limit the current to the desired value. The total impedance, Z_T (where $Z_T = Z_1 + Z_2 + Z_0$ and $Z_1 = Z_2$) necessary to limit the fault current to (N) times the transformer rating must be equal to $\frac{100}{N}$ percent using the three phase kva rating of the grounding bank as a base. The value of N can be determined from Fig. 4, Curve B. If N is taken as 13 times the three phase kva rating of the grounding bank then $Z_T = \frac{100\%}{13}$ or 7.6969% expressed in terms of the grounding bank capacity.

In the case under consideration the system positive sequence impedance (Z_1) is 20% expressed to a 20,000 kva base. Converting this 20% impedance to the unknown kva (X) rating of the grounding bank it becomes $Z_1 = (\frac{X}{20,000} \cdot 20)$.

$$= .001X \text{ per cent}$$

$$\text{Since } Z_1 = Z_2 \text{ then } Z_1 + Z_2 = 2(\frac{X}{20,000}\ 20) \text{ per cent}$$

$$\text{or } Z_1 + Z_2 = .002X \text{ per cent}$$

The impedance of transformers which are commercially available range from approximately 2.5% for distribution transformers to 10% for network transformers. The common impedance range for power transformers is from 5% to 7.5%. Since these impedances are expressed to the transformer kva as a base they may be substituted for Z_0 as expressing the impedance of the grounding bank with an unknown (X) kva base.

$$\text{Since } Z_T = Z_1 + Z_2 + Z_0$$

$$\text{and } Z_T = \frac{100}{N} = \frac{100}{13} \text{ or } 7.6969\%$$

then $Z_1 + Z_2 + Z_0 = 7.6969\%$ expressed to the grounding bank kva as a base when the value of "N" is 13.

It has already been shown that $Z_1 + Z_2$ expressed to the grounding bank kva base (X) is equal to .002X% and it has been

stated that the impedance of the grounding bank transformers may be substituted directly for Z_0. Rewriting the equation

$Z_T = Z_1 + Z_2 + Z_0$ and substituting the above values using 5% as Z_0, it becomes

7.6969% = .002X% + 5%. Transposing and solving for (X) the unknown kva of the grounding bank using 5% impedance transformers

$$.002X = 7.6969-5$$
$$X = \frac{7.6969-5}{.002}$$
$$X = 1348 \text{ kva}$$

1349
2.6969
2

For general use the above equation can be rewritten as

$$X = \frac{\frac{100}{N} - Z_0}{2Z_1} B$$

$$\text{or } X = \frac{7.6969 - Z_0}{2Z_1} B$$

Where X is the kva of the grounding bank

Z_0 is the impedance of the grounding bank transformers

B is the kva base in terms of which the supply system impedances are expressed

Z_1 is the positive phase sequence impedance of the supply system expressed in per cent of B

N is maximum permissible kva load on the grounding bank divided by the kva rating of the bank. The value of N may be varied, in the above equation it is taken as 13.

As the impedance of the grounding bank transformers is increased the required kva capacity decreases. The following tabulation shows the grounding bank capacity required, using various transformer impedances, as well as other pertinent data when the value of N is 13.

%Z of Grounding Bank Transformers	Grounding Bank Kva (X) Capacity Required to Limit Load to 13 Times Rating	% Z_1 Expressed to Grounding Bank Kva (%Z_1 = .001X)	Ratio Z_0/Z_1
5.0	1348	1.348	3.7:1
5.5	1098	1.098	5.0:1
6.0	848	.848	7.0:1
6.5	598	.598	10.8:1

Checking the ratios of Z_0/Z_1 shown in the above tabulation against data shown in Fig. 3 it is found that the highest transformer impedance which can be used is less than 6.5% if the voltage to neutral on the unfaulted phases is not to exceed 150% of normal during maximum phase to ground faults. It should also be noted that unbalanced load limitations require a minimum grounding bank capacity of 900 kva as stated under section 4 a.

The above statement should not be interpreted to mean that transformers having an impedance greater than approximately 6.0% could not be used in the grounding bank under consideration. It does mean that if it is desired to load the grounding bank to 13 times rated capacity during maximum phase to ground faults, transformer having an impedance of slightly less than 6.0% must be used.

If the value of N is taken as less than 13, higher impedance transformers can be used in the grounding bank but the required kva capacity will be increased.

The data shown in the following tabulation was calculated using 8 as the value of N:

%Z of Grounding Bank Transformers	Grounding Bank Kva (X) Capacity Required to Limit Load to 8 Times Rating	% Z_1 Expressed to Grounding Bank Kva ($\%Z_1 = .001X$)	Ratio Z_0/Z_1
5.0	3750	3.75	1.33:1
5.5	3500	3.50	1.57:1
6.0	3250	3.25	1.85:1
6.5	3000	3.00	2.16:1
7.0	2750	2.75	2.54:1
7.5	2500	2.50	3.00:1
8.0	2250	2.25	3.55:1
8.5	2000	2.00	4.25:1
9.0	1750	1.75	5.15:1
9.5	1500	1.50	6.33:1
10.0	1250	1.25	8.00:1
10.5	1000	1.00	10.50:1

The data tabulated above show that by limiting the grounding bank maximum fault load to only eight times its rating 10% impedance transformers can be used without exceeding the allowable voltage of 150% normal on the unfaulted phases during phase to ground faults. The use of such high impedance transformers will necessitate the use of greater kva capacity and will materially increase the cost of the grounding bank.

5. Determining the kva Capacity (X) of Smallest Permissible Grounding Bank, Based on Fault Current Only

When purchasing equipment for a grounding bank it will be desired, in the interest of economy, to keep the kva capacity as low and the impedance as high as safety will permit. The minimum

capacity and maximum impedance are indicated by the maximum permissible value of N (Fig. 4) and the maximum permissible ratio of Z_0/Z_1 (Fig. 3). These values are constant under all conditions, the maximum permissible value of N being 13 and the maximum permissible ratio Z_0/Z_1 being 9.

Using the maximum permissible value of N or 13 the expression $Z_T = \frac{100}{N}$ per cent becomes $Z_T = \frac{100}{13}$ or 7.6969% expressed in terms of the grounding bank kva.

Since $Z_T = Z_1 + Z_2 + Z_0$ and $Z_1 = Z_2$, if $Z_0/Z_1 = 9$, then $Z_1 = \frac{Z_0}{9}$, $Z_2 = \frac{Z_0}{9}$ and $Z_T = \frac{Z_0}{9} + \frac{Z_0}{9} + \frac{Z_0}{1}$ or $Z_T = \frac{11Z_0}{9}$

Transposing and solving Z_0 in terms of Z_T

$$Z_0 = \frac{9Z_T}{11} \text{ or } Z_0 = .818Z_T$$

It follows that the impedance of the smallest permissible grounding bank must be .818 x 7.6969% or 6.2960% expressed in terms of its own kva base.

The kva capacity X of the smallest permissible grounding bank at the substation under discussion can readily be determined by the use of the equations already given.

Where $Z_T = Z_1 + Z_2 + Z_0$ and Z_T also = 7.6969%

If Z_0 = 6.2960% then $Z_1 + Z_2$ = 7.6969 - 6.2960 or 1.4009%

It has already been determined that $Z_1 + Z_2$ at the substation is equal to .002X% expressed in terms of the grounding bank kva (X) when the positive sequence impedance of the system (Z_1) is 20% at the point at which the grounding bank is to be installed, expressed in terms of a 20,000 kva base.

Therefore .002X% = 1.4009%

$$X = \frac{1.4009}{.002}$$

$$X = 700 \text{ kva}$$

For general use the above equation can be rewritten as

$$X = \frac{.70045}{Z_1} B$$

Where X is the kva of the smallest permissible grounding bank with an impedance of 6.2960%

B is the kva base in terms of which the supply system impedances are expressed

Z_1 is the positive sequence impedance of the supply system expressed in per cent of B

To determine the smallest permissible kva capacity in any grounding bank, assuming that fault current rather than load unbalance is the controlling factor, it is only necessary to substitute the values of Z_1 and B in the above equation and solve for X.

It follows from the above statements and conclusions that, for the smallest permissible grounding bank capacity on <u>any</u> system, either the impedance of the grounding bank transformers must be 6.2960% or the total neutral impedance (Z_0) expressed in terms of the grounding bank kva must be 6.2960%. This statement is, of course, true only so long as the highest permissible loading shown on Curve B, Fig. 4, and the highest permissible voltage rise shown on Fig. 3 are used as the basis for calculating the grounding bank capacity and impedance.

6. Use of Neutral Reactors

Neutral reactors are frequently used in conjunction with grounding banks permitting the use of lower impedance transformers than would otherwise be possible. To illustrate the method of calculating the characteristics of a neutral reactor assume that 3 - 300 kva 5% impedance transformers are available for use in the grounding bank at the substation already described. The total impedance ($Z_1 + Z_2 + Z_0$) necessary to limit the fault current to 13 times the grounding bank capacity has been determined to be 7.6969% expressed in terms of the grounding bank kva. $Z_1 + Z_2$ has been determined to be .002X% expressed in terms of the grounding bank kva. Expressing $Z_1 + Z_2$ in terms of a 900 kva bank it becomes .002 x 900 = 1.8%.

$$\text{Since } Z_0 = Z_T - (Z_1 + Z_2)$$

$$Z_T = 7.6969\%$$

$$\text{and } Z_1 + Z_2 = 1.8\%$$

$$\text{then } \quad Z_0 = 7.6969\% - 1.8\%$$

$Z_0 = 5.8969\%$, the minimum permissible zero sequence (Z_0) or neutral impedance when using 3 - 300 kva transformers as a grounding bank.

The rated zero sequence impedance of the transformers described is only 5% and in order to use them as a grounding bank a neutral reactor is required which has a zero sequence impedance of 5.8969 - 5% or .8969% expressed to a 900 kva base.

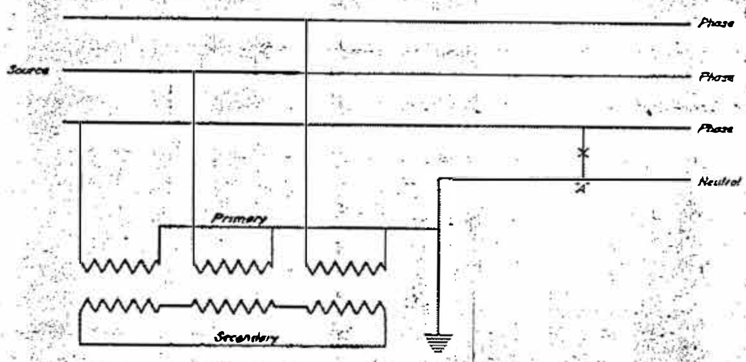
Reactors are usually rated in continuous load amperes and in short time load amperes. The reactors required in the case under discussion must have a continuous load ampere rating equal to or more than the neutral current during maximum unbalanced load. The maximum unbalanced load has already been determined to be 900 kva and the neutral current will be $\frac{900}{En}$ 1000 where En is the system phase to neutral voltage. If it is assumed that the system voltage is 13,200/7620 volts then the neutral reactor must have a continuous load ampere rating of not less than 118 amperes. The reactor must have an impedance of .8969% expressed in terms of the grounding bank capacity of 900 kva, that is, the voltage drop across the reactor must be .008969 x 7620 = 68.34 volts when the current value reaches 118 amperes. The impedance of the reactor must then be $\frac{68.34}{118}$ or .579 ohms.

Since the grounding bank load under maximum fault condition is (N) or 13 times normal, the reactor must have a short time rating (two seconds) of not less than 13 x 118 = 1534 amperes. The voltage drop across the reactor under maximum fault will be 68.34 x 13 or 888 volts which indicates the insulation level required in the reactor.

7. Conclusion

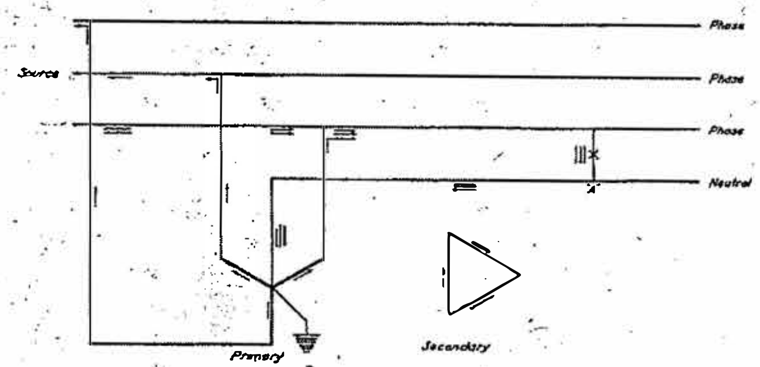
The foregoing discussion and examples serve to show that, having made basic assumptions concerning the maximum permissible loading on the grounding bank and the maximum permissible voltage rise on the unfaulted phases, the minimum kva capacity and maximum impedance of the grounding bank is readily obtained, needing only the positive sequence impedance (Z_1) of the supply system at the point at which the grounding bank is to be installed. The foregoing discussion and examples also show that many combinations of grounding bank capacity and impedance will serve equally well so long as their use does not violate the basic assumptions concerning maximum permissible transformer loading and maximum permissible voltage rise on the unfaulted phases.

August 24, 1942
Revised September 9, 1943



Schematic connection of grounding bank with primary connected in wye and neutral point grounded, no fuses in primary leads; secondary connected in delta and serving no load. "A" represents an unbalanced load or a phase to neutral fault.

FIG. 1



Showing current flow in grounding bank and in distribution system, due to an unbalanced load or phase to neutral fault. Unbalanced load or fault current is taken as 3I, each arrow represents I. For convenience the transformers are assumed to have a 1 to 1 transformation ratio.

FIG. 2

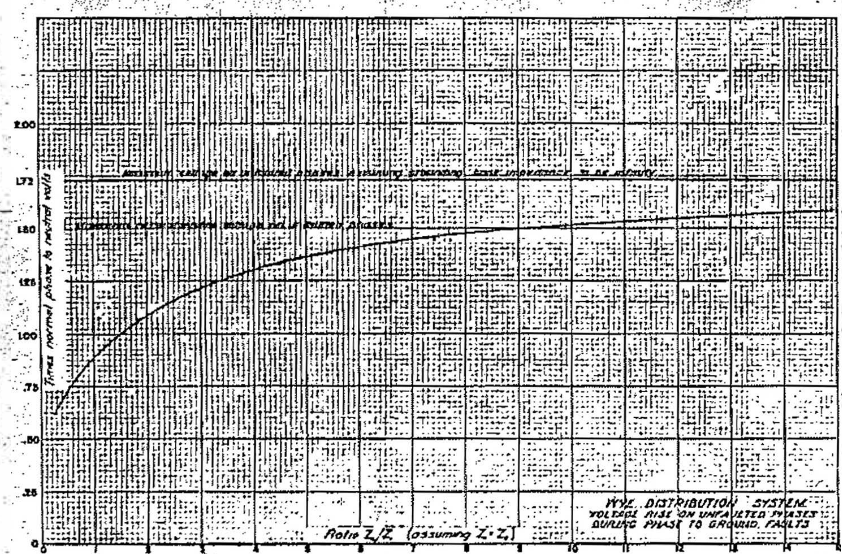


FIG. 3

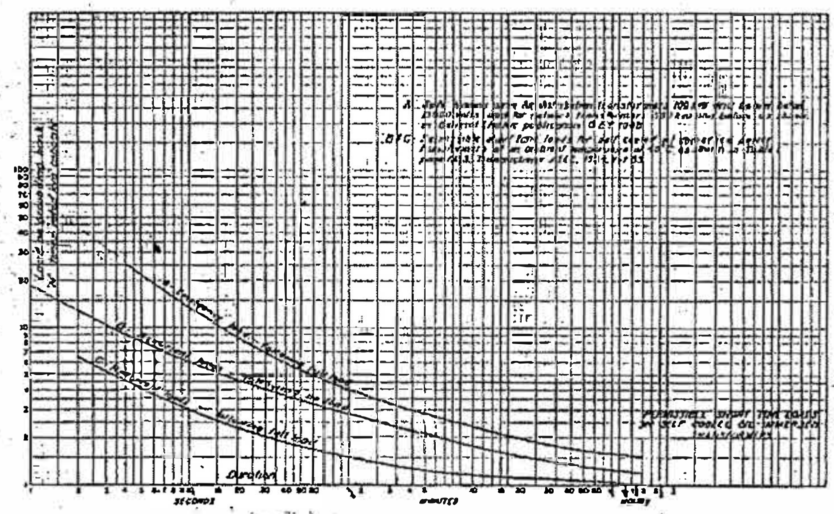


FIG. 4

GROUNDING BANK DATA